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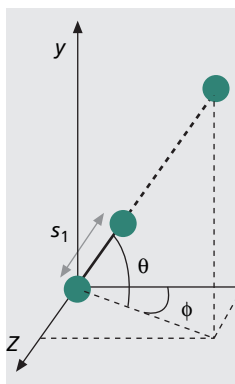
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HIGH-THROUGHPUT MULTIPLE-INPUT MULTIPLE-OUTPUT SYSTEMS FOR IN-HOME MULTIMEDIA STREAMING

IOANNIS SARRIS, ANDREW R. NIX, AND ANGELA DOUFEXI



Wireless systems based on MIMO technology have the potential to achieve increased spectral efficiency with no additional transmit power or bandwidth requirements. This can be achieved by exploiting the spatial subchannels between the multiple transmit and receive elements.

ABSTRACT

Wireless communication systems based on multiple-input multiple-output (MIMO) technology have the potential to achieve increased spectral efficiency with no additional transmit power or bandwidth requirements. This can be achieved by exploiting the spatial subchannels between the multiple transmit and receive elements. The enhanced performance of MIMO technology makes it a strong candidate for ad hoc systems requiring very high throughput, such as high-definition multimedia streaming in the home. In this article we compare the performance of conventional and newly proposed MIMO architectures for such applications. Specifically designed antenna arrays are proposed as a solution to significantly reduced MIMO performance in line-of-sight (LoS) conditions. To help in the design of such systems, the criterion for achieving maximum MIMO capacity in LoS is presented as a function of the transmitter-to-receiver separation distance, the array orientation and the element spacings. The performance of the LoS-enhanced proposal and the conventional system is quantified in terms of the channel capacity, the packet error rate (PER) and the throughput by employing a MIMO-enabled WLAN physical layer simulator. The results from MIMO measurements performed inside an anechoic chamber and in an indoor environment are presented to validate the theoretic predictions.

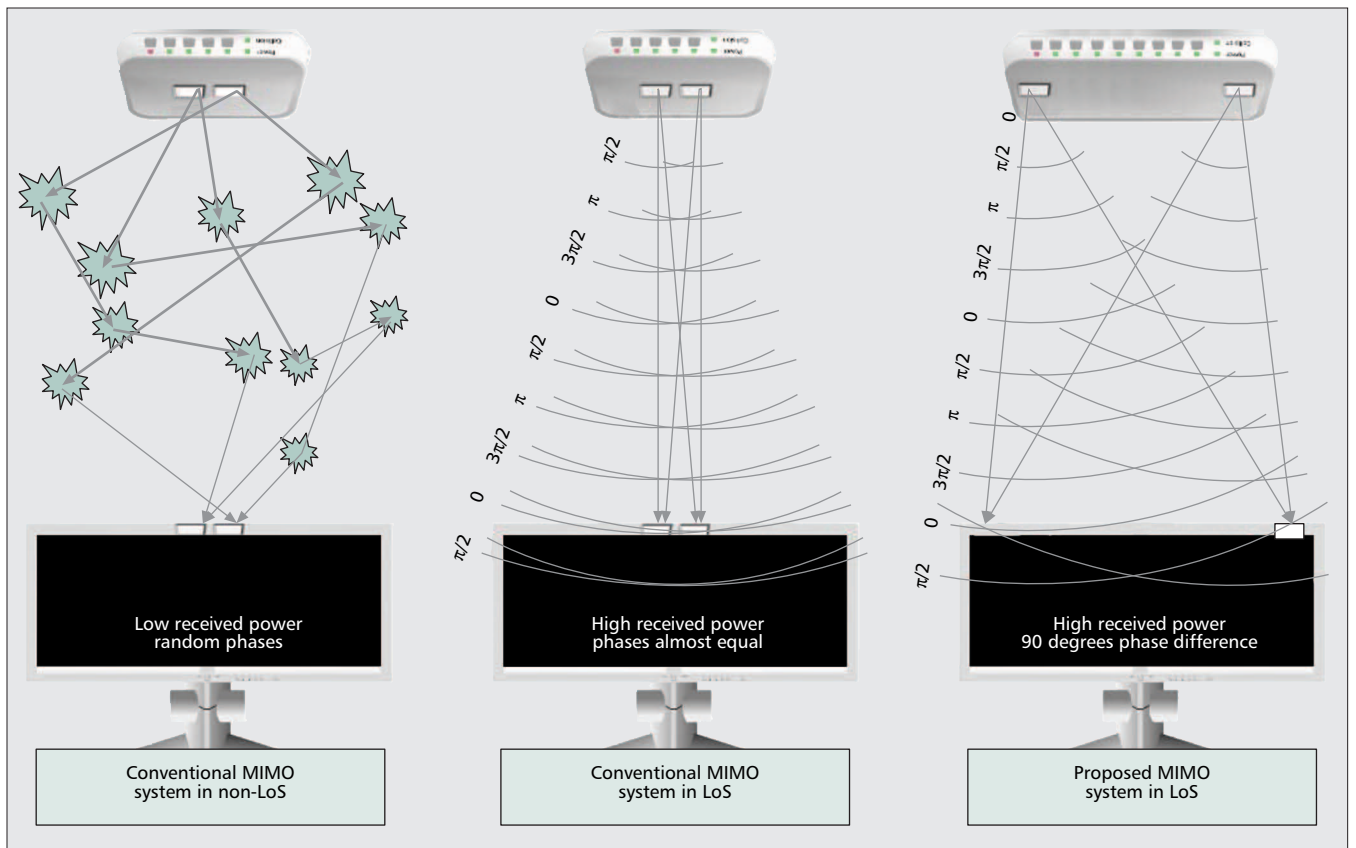
INTRODUCTION

The expanding penetration of ultra-broadband internet services (above 10 Mb/s) and the emergence of high-definition television (HDTV) are expected to dramatically increase the demand for high-data-rate wireless access and multimedia streaming in the home. A key technology that is expected to address the scaling limitations of future wireless communications systems for these applications is that of *ad hoc networks*. These networks consist of an autonomous collection of wireless devices that communicate over relatively bandwidth-constrained wireless links. Since the nodes are mobile, the network topology may change

rapidly and unpredictably over time. The network is decentralized; where all network activity including discovering the topology and delivering messages must be executed by the nodes themselves.

To address the capacity limitations of ad hoc networks in the home environment a system based on multiple-input multiple-output (MIMO) technology can be employed. Using this novel technology a considerable increase in the data rate can be achieved without the need for additional bandwidth (and in many cases additional transmit power). The method employs antenna arrays (which comprise multiple antenna elements) at both ends of the communications link. In this article we examine the performance of a particular MIMO scheme, known as spatial-multiplexing MIMO (SM-MIMO). In SM-MIMO the data is divided into a number of blocks (equal to the number of transmit elements). These blocks are independently and simultaneously sent from the transmit elements. At the receiver, appropriate signal processing is applied to differentiate the received data blocks originating from each of the transmit elements. The differentiation is made possible due to the (ideally) unique spatial signature acquired by each data block as a result of the propagation path taken to arrive at the receiver. Thus, under ideal propagation conditions a MIMO system with N transmit and N receive elements (from now on called an $N \times N$ system) can provide a linear increase in the data-rate with N [1]. This performance enhancement is called the multiplexing gain and is attributed to the exploitation of the spatial communication subchannels between all transmit and receive elements.

An example where this gain can be fully exploited is in a (non-LoS) rich-scattering environment. In such environments there are a significant number of active scatterers and therefore a large number of independent communications paths exists between the transmit and receive antenna elements (Fig. 1). At the receiver, the spatial signature of each transmitted signal is unique, and the signals sent from different antenna elements can be easily differentiated [2]. However, in a non-LoS environment the increased multiplexing gain comes at the cost of a reduction



■ **Figure 1.** Graphical representation of a non-LoS rich-scattering scenario, a conventional MIMO system in LoS and the proposed MIMO system in LoS.

in the mean received signal power, usually expressed as the signal-to-noise ratio (SNR), due to the energy lost from transmissions, reflections, and other propagation effects. Moreover, the instantaneous received signal power experiences a significant fluctuation due to the constructive and destructive addition of the rays arriving at the receiver with random phases (multipaths). These random fluctuations make the recovery of the transmitted data stream more difficult.

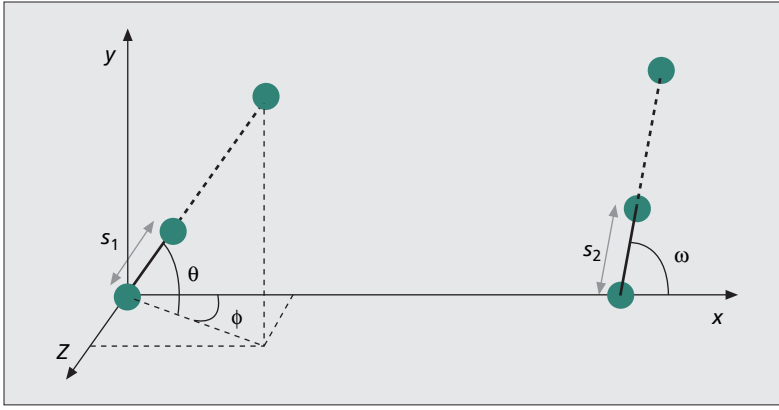
In conventional single-input single-output (SISO) systems (which use a single transmit and receive antenna) the ideal propagation scenario is an environment where the transceivers are placed in LoS. In such environments the mean received power is high and the multipath fading is very low due to the dominance of the LoS signal over any multipath components. However, in MIMO systems a LoS environment normally results in significantly reduced performance due to the minimal spatial multiplexing gain offered from the LoS rays [3]. This occurs because in conventional MIMO systems the interelement array spacing is normally of the order of one wavelength; for an 802.11a WiFi system this corresponds to approximately 6 cm, which is usually very small compared to the transmitter-to-receiver (T-R) separation distance. Thus, the LoS signals arrive at the receive elements with almost identical characteristics and the differentiation between signals originating from different transmit elements is very difficult (Fig. 1).

The trade-off between SNR and multiplexing gain in the aforementioned scenarios has created an interesting debate on the benefits of MIMO

for ad hoc applications [4]. In this article we present a third LoS scenario where a proposed system *simultaneously* achieves high received power levels and high multiplexing gain. This is realized by employing antenna array geometries that deliberately create unique spatial signatures on the received signals (Fig. 1) [5, 6]. Even though previous research has already shown that this is possible, it was only recently that a simple array design methodology was introduced to achieve these benefits in practice [7]. This methodology is formulated by a maximum capacity criterion in LoS that is expressed as a function of the interelement distances, the arrays' orientations and the T-R separation distance. In this article we present a number of architectures designed with this criterion and compare their performance with conventional MIMO systems under various propagation conditions. The results are quantified in terms of the MIMO channel capacity, the packet-error rate (PER) and the link throughput. The latter are acquired using a MIMO enhanced 802.11a physical-layer simulator with channel responses obtained from measurements and appropriate statistical models.

HIGH-CAPACITY MIMO IN LOS

The proposed array architecture is based on the principle that the performance can be increased to ultimately reach a maximum value if the interelement spacing is increased at one or both of the arrays. It has been shown that the maximum performance in an $N \times N$ system occurs



■ Figure 2. Array geometries corresponding to the maximum capacity criterion.

when the arrays have spacings that result in a phase difference of π/N between the received signals (Fig. 1) [7]. The received signals are then said to be *orthogonal* and in a strong LoS environment the performance of the system is equivalent to N times that of a SISO system. This level of performance is *higher* than that of the (conventionally ideal) rich-scattering scenario.

MAXIMUM MIMO CAPACITY CRITERION IN LoS

To design optimal systems for LoS MIMO communications, we use the simplified maximum capacity criterion derived in [7]. For the case of an $N \times N$ system with uniform linear arrays (ULAs) at both ends of the communication link (Fig. 2), this criterion can be expressed in terms of the interelement spacings s_1, s_2 , the transmitter-to-receiver separation distance D , the wavelength λ (which corresponds to the carrier frequency), and the angles θ and ω that correspond to the elevation of the arrays as follows:

$$s_1 s_2 = \lambda \left(\frac{1}{N} + r \right) \frac{D}{\sin \omega \sin \theta} \quad (1)$$

where r is any positive integer or zero. The above equation has infinite solutions that correspond to the values of r . However, the most practical solution corresponds to $r = 0$, since the array length is then at a minimum.

The significance of the maximum capacity criterion for LoS is that it presents a straightforward method for calculating the required spacing to achieve the optimal performance for a given array orientation and T-R separation distance. It is interesting to note that the required spacing per element decreases with increasing N , resulting in higher space-efficiency for increased N .

CAPACITY PERFORMANCE

The maximum capacity criterion defines MIMO configurations that yield very high performance in LoS conditions. However, these configurations correspond to fixed structures that are optimized for specific points in space. Most practical applications require coverage over an area, rather than a specific point. Therefore, in this section we analyze the suboptimum area performance for systems designed using the maximum capacity criterion. In detail, we examine the sensitivity of the capacity to displacements from the optimal

location. We also consider the use of arrays with suboptimal orientations.

We assume the use of a two-element access point (AP) positioned at a height of 3 m (i.e., $D = 3$ m) above an identical two-element mobile terminal (MT). The MT is then moved over an area of 20 m^2 (centered directly below the AP). Both arrays are assumed to remain parallel to the ground plane at all times. The interelement spacing at both arrays is 30 cm, which is optimal for the case where the MT is placed directly below the AP. The capacity of the system is calculated from the pure LoS geometric channel model presented in [2] and the results are shown in Fig. 3. The sensitivity of the capacity to array orientation is quantified for four different MT orientations.

For $\theta = 90^\circ$, the capacity can be seen to reduce *gradually* as the MT moves away from the optimum location (i.e., the center of the graph). Over an elliptical area of approximately 21×9 m, the capacity has a value of at least 90 percent of the maximum (with the maximum occurring directly beneath the AP). However, the capacities for $\theta = 60^\circ, 30^\circ$, and 0° demonstrate the sensitivity of the system to the orientation of the arrays. This sensitivity can be significantly reduced by employing an adaptive three-element uniform circular array (UCA) structure at one end of the communications link. The advantage of this architecture is that a subset of two elements can always be selected so that the angle θ between this subset of elements and the two-element array is always less than or equal to 60° . Thus, by employing suitable switching algorithms at the UCA, the capacity can maintain values near to the maximum irrespective of the angle θ .

The above three-element UCA system was modeled at the AP and the capacity using a two-element MT was evaluated (assuming optimal element selection). The capacity variation over the floor space for such a system is shown in Fig. 3 for $\theta = 0^\circ$ and $\theta = 90^\circ$. It is obvious that the capacity variation for this adaptive configuration is very small. The expense of an additional antenna element and the increased complexity of element switching are expected to be acceptable for an AP device.

LINK-LEVEL PERFORMANCE ASSESSMENT

THEORETIC RESULTS

Previous work has shown that there is a one-to-one relationship between the capacity and link-level performance of a MIMO system in pure LoS [8]. Therefore, it is expected that our proposed array design methodology will also apply for maximizing the resulting MIMO link-level performance. To validate this hypothesis, the performance of our proposed system is now compared in LoS scenarios to that of a standard MIMO array (which uses closely spaced elements). For this purpose, a MIMO enhanced 802.11a physical layer simulator was employed to evaluate the PER and throughput for a 2×2 MIMO system using measured and modeled channel responses (more details on the physical layer model can be found in [9]).

The capacity assessment in the previous section was based on a geometric LoS channel model (multipath components were not considered). Using this LoS model, the fundamental

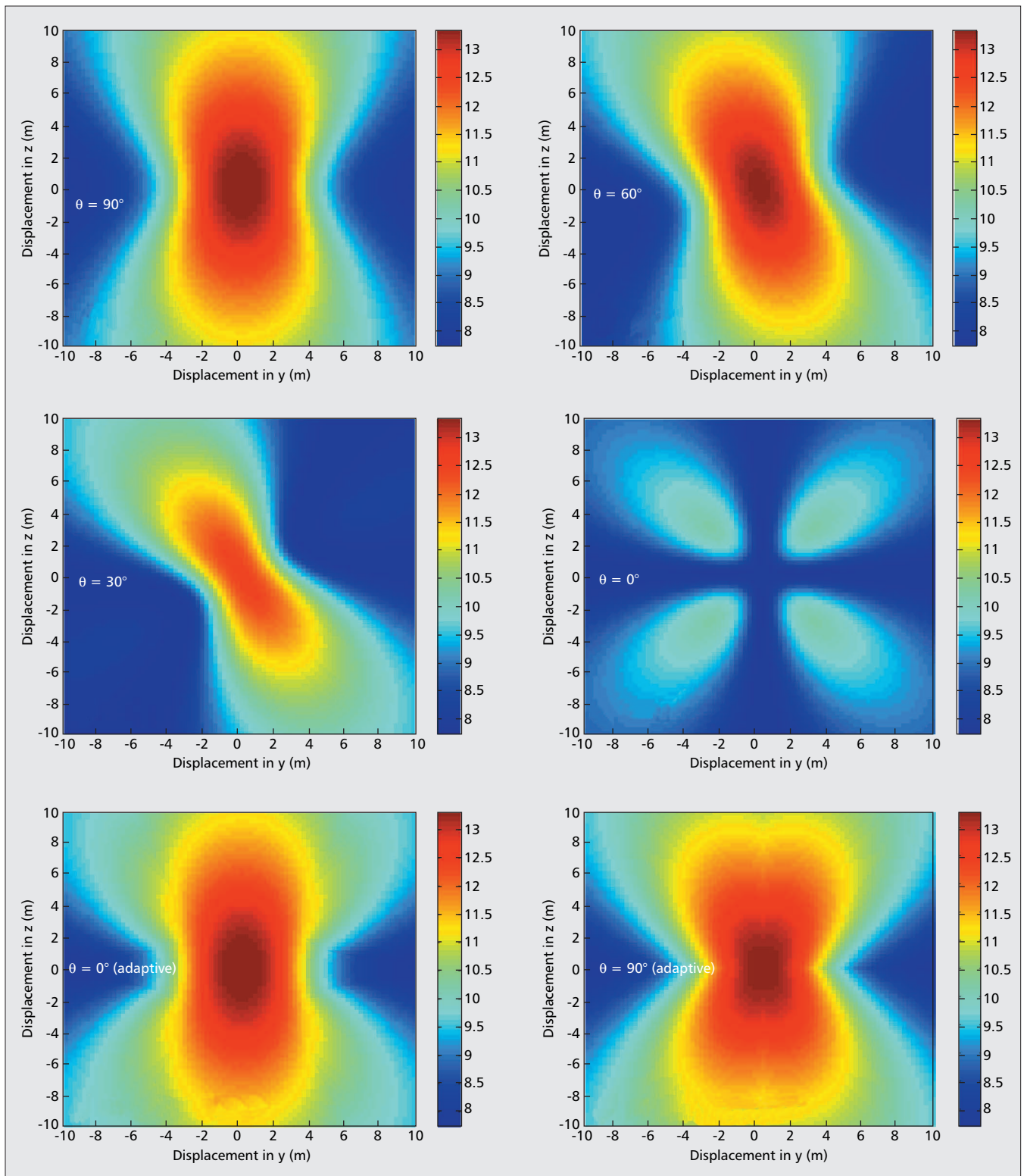
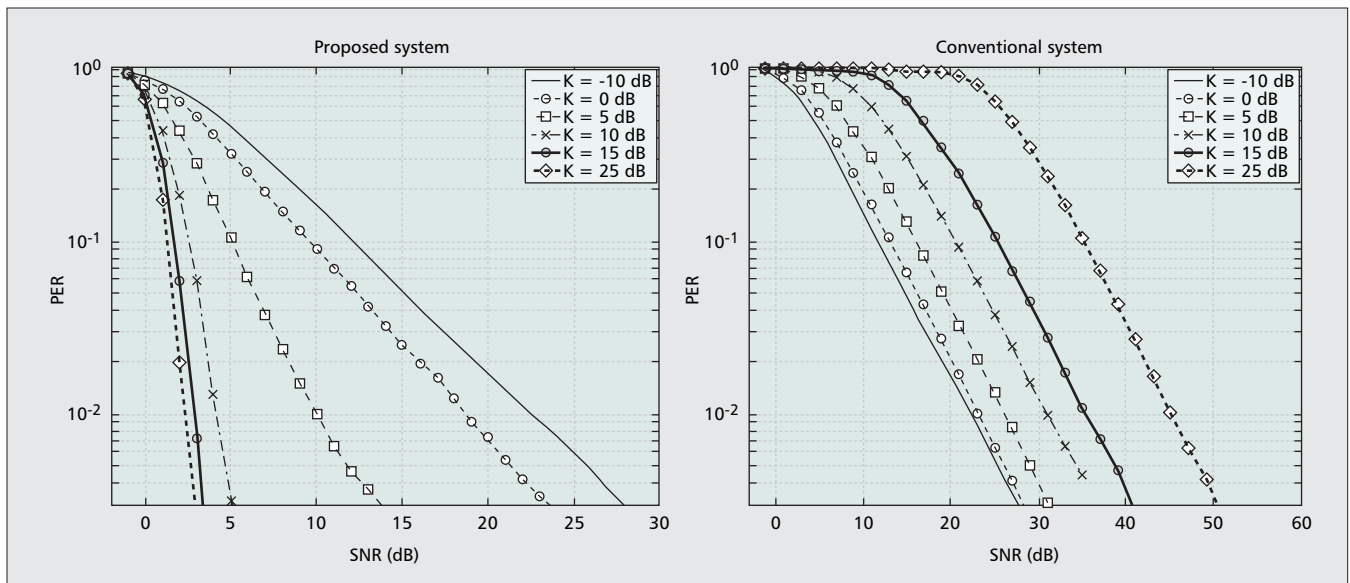


Figure 3. Capacity (bps/Hz) as a function of displacement on the z, y axes for a 2×2 system and an adaptive 2×2 system for various angles (SNR = 20 dB).

performance enhancements of the proposed architecture were investigated. We now evaluate the link-level performance of the proposed system under more realistic channel conditions. In detail, the effect of scattering is incorporated in a combined statistical and geometric model [2]. A large number of channel snapshots (10,000) were

acquired from this model to evaluate the performance of our systems at various ratios of LoS to scatter power. The metric used to describe this ratio is the Ricean K -factor, which in our case is defined as the ratio of the power in the LoS component to that of the scattered signals.

Two array architectures are assessed in this



■ **Figure 4.** PER performance of the proposed and conventional systems as a function of the K -factor.

study; the first corresponds to a system designed with the maximum capacity criterion and has an interelement spacing of 30 cm, while the second corresponds to a conventional system with array spacing of one wavelength (6 cm). For both systems the T-R separation distance is 3 m with parallel arrays (i.e., $\omega = 90^\circ$, $\phi = 0^\circ$, and $\theta = 90^\circ$).

The PER and throughput performance of the two systems are shown in Fig. 4 for various degrees of K -factor. A very significant performance gain is seen with the proposed system (especially for high values of K -factor). A phenomenal gain (relative to the standard array) of approximately 32 dB in SNR was observed for a K -factor of 15 dB. For lower K -factor values, the performance difference between the two architectures is reduced. In the limit, when the LoS signal is much weaker than the multipath scatter, the performances of the two systems converge to that of the rich-scattering scenario. It is possible to use our proposed system in LoS and NLoS environments, with significant gains shown in the former case.

In terms of throughput, once again a very significant performance enhancement is observed in the proposed system (Fig. 5). These results were obtained for a K -factor of 15 dB. The maximum throughput of 108 Mb/s was achieved at an SNR of around 17 dB, showing a 33 dB improvement over the standard MIMO technique. In fact, since the channel is orthogonal the throughput of the proposed system was found to be double that of the SISO system in LoS. Furthermore, the performance of the standard array system was found to be lower than a SISO configuration for most practical values of SNR (<30 dB).

MIMO MEASUREMENTS RESULTS

The results presented in the previous sections were based on statistical LoS MIMO channel models. To verify the validity of these predictions, we present the results from two sets of measurements that were performed at 5.2 GHz using a MEDAV RUSK BRI MIMO vector channel sounder (more details can be found in [10]). The first measurement was performed in an anechoic chamber,

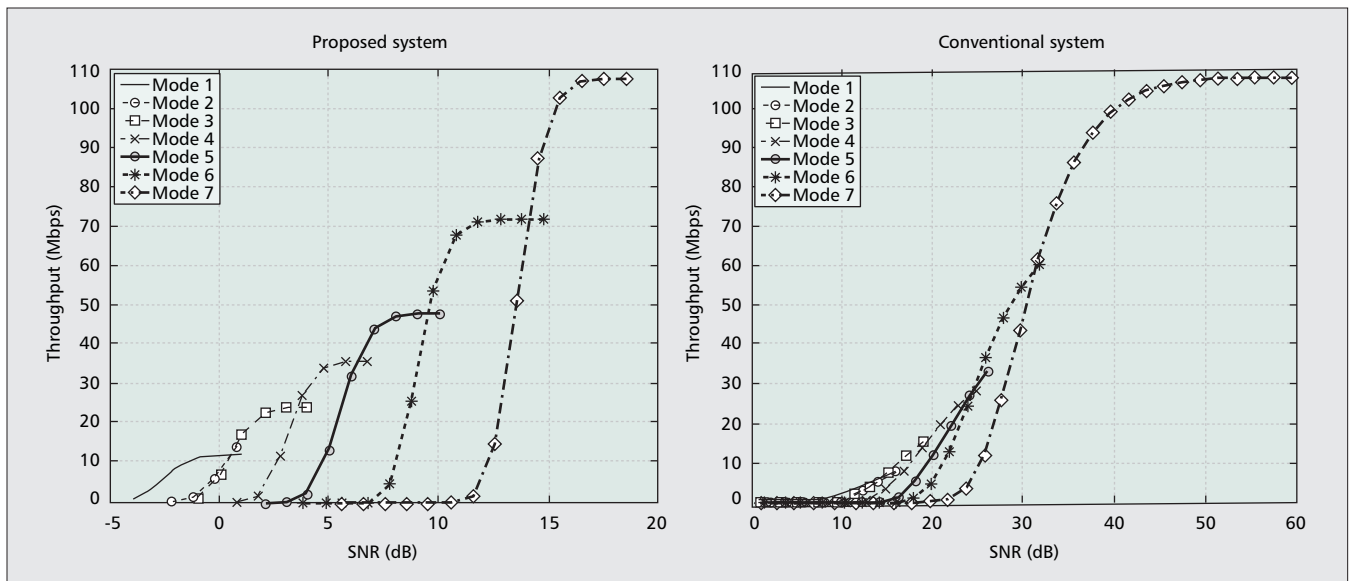
whereas the second was taken in an indoor office environment. In the former, there is virtually no scattering and thus the channel response is expected to closely approximate the free-space response. The results from these measurements demonstrate the fundamental validity of the proposed architecture. The second measurement set provides an insight into the expected performance of the proposed method in real indoor environments.

The antenna arrays employed in both measurements were two identical ULAs each composed of two patch antenna elements separated by 38 cm. At a carrier frequency of 5.2 GHz, this spacing corresponds to the first (i.e., for $r = 0$) solution of Eq. 1 for parallel arrays ($\omega = 90^\circ$, $\phi = 0^\circ$, and $\theta = 90^\circ$) and a T-R separation distance of 5 m. We recorded 1024 time snapshots of the MIMO channel response matrix. During post-processing, the channel matrices were normalized to maintain a unity transmit power. This ensures that the performance of both scenarios is studied independently of path loss.

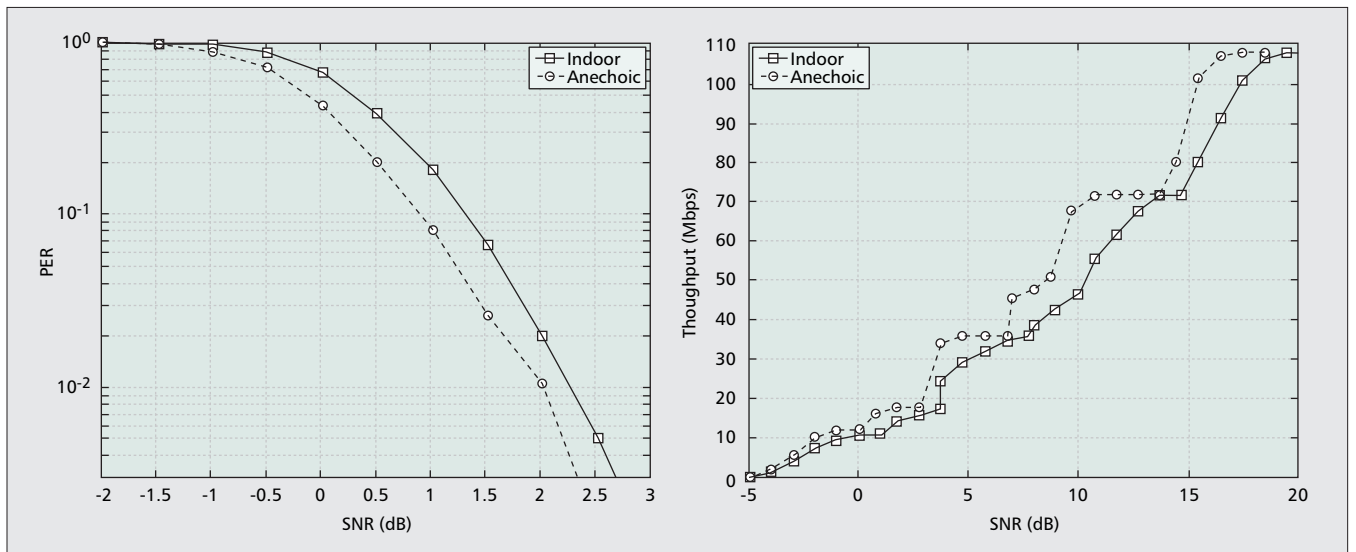
The resulting PER performances from the indoor and anechoic chamber measurements are shown in Fig. 6. For comparison purposes, the K -factors for both environments were calculated in the post-processing stage. These were found to be equal to 31.7 and 28.8 dB for the anechoic and the indoor office scenarios, respectively. Very close agreement with the theoretic PER results of Fig. 4 was observed. It is very interesting to note that the performance observed in the indoor environment was very similar (less than 0.5 dB difference) to the (ideal) scenario of the anechoic chamber. This implies that there is a high potential for the proposed method in indoor (home) scenarios. The same enhanced performance was also observed in terms of throughput. The throughputs in both measured scenarios were similar and showed very close agreement with the theoretic results in Fig. 5.

RESEARCH DIRECTIONS

Within the framework of FP6-IST-0028097 ASTRALS the authors plan to continue research in the following directions.



■ **Figure 5.** Throughput performance of the proposed and conventional systems ($K = 15\text{dB}$).



■ **Figure 6.** Measured PER and throughput performance of the proposed system.

DESIGN AND THEORETIC PERFORMANCE ASSESSMENT OF OPTIMAL MIMO STRUCTURES

Using the previously developed theory a number of MIMO uniform linear array (ULA) and uniform circular array (UCA) optimal structures will be developed at the University of Bristol. Initially, the performance of these architectures will be investigated theoretically in terms of the MIMO channel capacity using appropriate LoS channel models. The link-level performance will also be evaluated using MIMO extended WiFi and WiMax physical layer models. The proposed system will be assessed under various propagation conditions and in both optimal and suboptimal positions and orientations. Switching between a subset of the total number of elements on one or both ends of the communications link will also be considered as a way of maximizing the capacity and removing the sensitivity of the system to orientations or displacements from the optimal point.

IMPLEMENTATION AND ASSESSMENT OF OPTIMAL ARRAY STRUCTURES

Following theoretic studies on the performance of the proposed and conventional array architectures, a number of attractive architectures will be selected for prototype implementation. The performance of the developed structures will firstly be evaluated using MIMO measurements from a MEDAV MIMO channel sounder in an in-home environment. Channel data will be collected for both LoS and NLoS propagation conditions. The measured channel responses will be post-processed and the corresponding link-level performances expressed in terms of the channel capacity, PER, and throughput. The results from this study will be compared to earlier theoretic results. The performance of conventionally spaced arrays will also be evaluated using the same measurement methodology.

The proposed system showed a very significant performance improvement over conventional MIMO systems in LoS. At high values of K-factor, the proposed system achieved a throughput that was several times higher than that achieved using a conventional array system at the same SNR.

DEVELOPMENT OF A MIMO TEST BED

The performance of the proposed architectures will be assessed using the University of Bristol's Elektrobitt C8 MIMO channel emulator. This equipment will be configured as a MIMO real-time transmission test-bed. In particular, software generated MIMO data packets will be sent at RF over a range of array configuration (both proposed and conventional). The Elektrobitt hardware will be used to transmit and receive these data bursts in real-time in a number of indoor propagation scenarios. The received data will be stored to hard disk and post processed to determine the PER and throughput performance.

DEVELOPMENT OF THEORY AT 60 GHz FOR WIRELESS VIDEO STREAMING

The suitability of MIMO for short-range indoor systems operating at 60 GHz will also be assessed within ASTRALS. The major benefit of this frequency band is the large amount of unlicensed bandwidth (>3 GHz) that exists throughout the world. The main difference between the 5 and the 60 GHz frequency bands from a propagation point of view is that, in the latter, the free-space path loss and reflection/transmission losses are much higher. The effect of oxygen absorption further limits the range of 60 GHz systems. As a result, the 60 GHz frequency band is considered as a candidate frequency for future short-range communications (up to 5m). At these short ranges, the transmit and receive antennas are very likely to be in LoS. Furthermore, a strong LoS is considered essential to provide a useable signal level. Finally, at 60 GHz the small wavelength benefits the practicality of our proposed method, since the array size can be extremely compact.

CONCLUSIONS

The performance of a novel architecture for MIMO communications in an indoor environment was assessed by means of stochastically modeled and measured MIMO channels using an 802.11a WLAN physical-layer simulator with SM-MIMO extensions. The proposed system showed a very significant performance improvement over conventional MIMO systems in LoS. At high values of K-factor, the proposed system achieved a throughput that was several times higher than that achieved using a conventional array system at the same SNR.

The theoretic predictions were validated using MIMO channel measurements. The simulated results were recreated in practice using arrays designed with the proposed architecture. A difference of less than 0.5 dB was observed between the PER curve for the measured channels and that of the theoretic predictions.

Future research directions have also been described with key activities including the design and implementation of optimal MIMO structures for in-home environments along with the theoretical and practical assessment of these

structures in real environments. Application of these methods in the emerging 60 GHz band is also under consideration.

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BIOGRAPHIES

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